Phytoremediation of Xenobiotics: Principles and Applications in Environmental Pollution Removal

Hadia Hemmami, Ilham Ben Amor, Soumeia Zeghoud, Abdelkrim Rebiai, Bachir Ben Seghir, Imane Kouadri, and Mohammad Messaoudi

1 Introduction

Global human life and sustainability are being negatively impacted by environmental contamination (Manisalidis et al. 2020). Agricultural intensification (Mózner et al. 2012), rapid urbanization, and industrialization (Wu et al. 2016) are just a few of the anthropogenic activities that are seriously contaminating the environment by metalloids, heavy metals (He et al. 2015), radionuclides (He et al. 2019), organic substances (Afzal et al. 2014), agrochemicals (Malik et al. 2017), and spills of oil (Ron and Rosenberg 2014). Soil contamination has been caused by mining operations, the discharge of effluents from businesses and homes, the extensive usage of fertilizers, irrigation, and pesticides, with water that is polluted (Tang et al. 2015). Numerous soil characteristics are impacted by mining, such as cation exchange capacity, electrical conductivity, and pH (Saleem et al. 2020a, b).

H. Hemmami · S. Zeghoud
Department of Process Engineering and Petrochemical, Faculty of Technology,
University of El Oued, El Oued, Algeria

Renewable Energy Development Unit in Arid Zones (UDERZA), University of El Oued,
El Oued, Algeria

Laboratory of Applied Chemistry and Environment, Faculty of Exact Sciences,
University of El Oued, El Oued, Algeria

I. B. Amor
Department of Process Engineering and Petrochemical, Faculty of Technology,
University of El Oued, El Oued, Algeria

Renewable Energy Development Unit in Arid Zones (UDERZA), University of El Oued,
El Oued, Algeria

Laboratory of Biotechnology Biomaterials and Condensed Materials, Faculte de la
Technologie, University of El Oued, El Oued, Algeria

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High levels of pollution cause biomagnification across the food chain, which has an impact on the entire planet's biota. Reverse osmosis (Al-Alawy and Al-Ameri 2017), chemical precipitation (Huang et al. 2017), ion exchange (Levchuk et al. 2018), adsorption, and solvent extraction (Burakov et al. 2018) are only a few of the methods used to eliminate contaminants from the environment. These methods are typically not sustainable and involve extensive maintenance costs and functions. As a quick and inexpensive alternative to decontaminating heavy metal-contaminated locations, one of the most ecologically friendly techniques is phytoremediation strategies to combat pollution in urban systems (Fig. 1) (Liu et al. 2020). Since there is no need to alter the soil's structure, this approach has little effect on the environment (He et al. 2012). After phytoremediation is finished, the area can be used again for farming (Pusz et al. 2021). This innovative approach eliminates the toxicity of pollutants from contaminated places using hyperaccumulators (Nedjimi 2020).

In order to further improve the phytoremediation of pollutants in urban systems, this chapter aims to consolidate information on the mechanisms that plants employ and how choosing the right species might optimize each mechanism's advantages. The findings are summarized on the issue of phytoremediation and how it has been used to remove various toxins from the environment after searching published literature using several online search engines.

A. Rebiai
Renewable Energy Development Unit in Arid Zones (UDERZA), University of El Oued,
El Oued, Algeria

Laboratory of Applied Chemistry and Environment, Faculty of Exact Sciences,
University of El Oued, El Oued, Algeria

Chemistry Department, Faculty of Exact Sciences, University of El Oued, El Oued, Algeria

B. Ben Seghir (✉)
Department of Process Engineering and Petrochemical, Faculty of Technology,
University of El Oued, El Oued, Algeria

Renewable Energy Development Unit in Arid Zones (UDERZA), University of El Oued,
El Oued, Algeria

Laboratory of Industrial Analysis and Materials Engineering (LAIGM),
University of 8 May 1945, Guelma, Guelma, Algeria
e-mail: bbachir39@gmail.com

I. Kouadri
Renewable Energy Development Unit in Arid Zones (UDERZA), University of El Oued,
El Oued, Algeria

Department of Process Engineering, Faculty of Science and Technology,
University of 8 May 1945, Guelma, Guelma, Algeria

M. Messaoudi
Chemistry Department, Faculty of Exact Sciences, University of El Oued, El Oued, Algeria

Nuclear Research Centre of Birine, Ain Oussera, Djelfa, Algeria

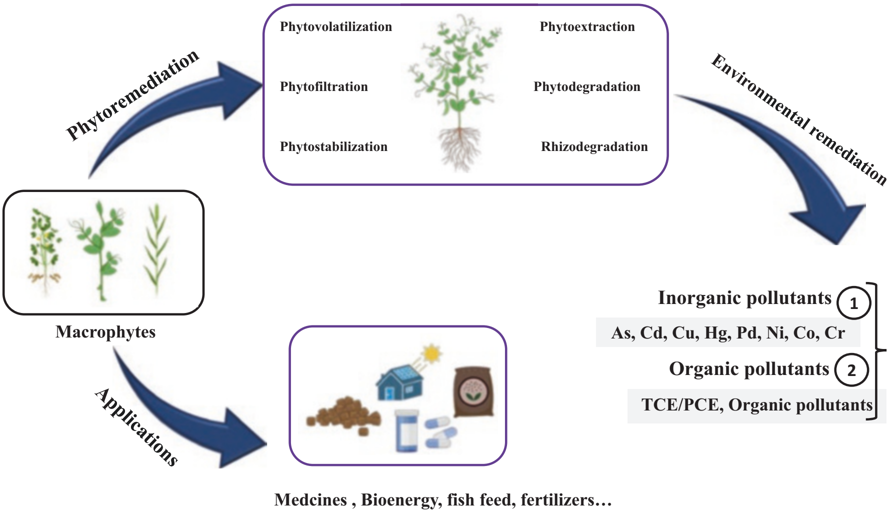

Fig. 1 Perspectives on employing macrophytes in phytoremediation to remove heavy metals and other contaminants

2 Phytoremediation of Xenobiotic Pollutants (Detoxification of Xenobiotics by Plants)

Phytoremediation is a term that combines the Latin suffix *remedium*, which is to mean "restore," with the Greek word *phyto*, which means "plant." Natural and transgenic plants are both used in the phytoremediation method to clean up contaminated habitats (Tripathi et al. 2020). The use of hyperaccumulators for the extraction, absorption, and degradation of hazardous contaminants and toxic metals was originally described in 1983 (Sarwar et al. 2017). As illustrated in Table 1, the process employs a variety of phytotechnologies based on naturally occurring and genetically engineered plant species to eliminate xenobiotics in urban systems (Kushwaha et al. 2018).

The process of phytoremediation can be carried out utilizing both in situ and ex situ techniques. Since the in situ application methods reduce the growth of pollutants in water, soil, and volatilized waste, the risk to the surrounding environment is automatically reduced (Raskin and Ensley 2000). The key parameters for ex situ bioremediation include the contaminated site's geographic location, treatment costs, pollutant types, and degree of pollution. Compared to other remediation methods used posttreatment, phytoremediation is more cost-effective (Cristaldi et al. 2017) since it is a straightforward, labor-free technique requiring no installation of specialized equipment. Where other regularly used approaches are ineffective and too expensive, the process can be used to a great extent (Leguizamo et al. 2017).

Avoidance and tolerance are two defense strategies that can be used for the application of the phytoremediation approach for the cleanup of heavy metals (Thakur et al. 2016). These two techniques are employed by plants to maintain heavy metal

Table 1 Plants that are used in mechanisms for phytoremediation

Phytoremediation mechanisms	Scientific name	Common name	Contaminants	Results	Reference
Phytoextraction	*Sesbania drummondii*	Rattlebush	Pb	EDTA increased Pb absorption and buildup	Barlow et al. (2000)
	Lactuca sativa Higher	Lettuce	Ni, Co, and Fe	Decreased intrinsic velocity and increased absorption capacity	Hernández et al. (2019)
	Pelargonium hortorum	Geranium	Pb	Used bacteria that are Pb-tolerant	Manzoor et al. (2019)
	Nicotiana tabacum	Tobacco	Cd	Higher in leaves and stems	Y. Yang et al. (2019a)
	Zea mays	Corn	Ti, Pb	Chelators supported Pb and Ti phytoextraction	Huang et al. (2019)
Phytostabilization or phytoimmobilization	*Eupatorium cannabinum*	Holy rope/ hemp-agrimony	As	Phytostabilization was favored by the addition of 20 mg/L of citric acid (CA)	González et al. (2019)
	Kosteletzkya pentacarpos	Seashore mallow/ coastal mallow	Zn, Cd	Salinity protects plants from the toxicity of metals. Zn resistance is promoted by cytokinin	Zhou et al. (2019)
	Salix sps.	Willow	Cd	Salix does not flood; hence, it has a greater BCF than species that do	W. Yang et al. (2019b)
	Solanum nigrum	Black nightshade	Cu, Zn, Cd	Recommend addition of 10% biochar/attapulgite	X. Li et al. (2019)
	Helianthus annuus	Sunflower	As, Cu, Hg, Pb, Zn, Ni, Cd	Vermicompost is used as a supplement, typically for metal contamination with low levels	Jadia and Fulekar (2008)

Rhizofiltration	*Azolla caroliniana*	Carolina mosquito fern/water velvet	As	BCF:0.000397	Favas et al. (2012)
	Callitriche lusitanica	Water starwort	As	BCF:0.002346	Favas et al. (2012)
	Callitriche stagnalis	Pond-water starwort	U	BCF:0.00194841	Pratas et al. (2012)
	Fontinalis antipyretica	Water moss	U	BCF:0.00023479	Pratas et al. (2012)
	Lemna minor	Duckweed	U	BCF:0.000529	Pratas et al. (2012)
	Callitriche brutia	Water starwort	As	BCF:0.000523	Favas et al. (2012)
	Ranunculus trichophyllus	Threadleaf corwfoot	As	BCD:0.00054	Favas et al. (2012)
Phytovolatilization	*Juncus effuse*	Common rush	Ammonium	Released methane	Wiessner et al. (2013)
	Brassica juncea	Mustard	Se	*Brassica* spp. able to phytovolatilize selenium	Banuelos et al. (1997a, b)
	Scirpus robustus	Saltmarsh bulrush		Wetland plants	Arthur et al. (2005)
	Myriophyllum brasiliense	Parrot’s feather		Wetland plants	Pilon-Smits et al. (1999)
	Juncus xiphioides	Iris-leaved rush		Wetland plants	
	Typha latifolia	Broad leaf cattail		Wetland plants	

(continued)

Table 1 (continued)

Phytoremediation mechanisms	Scientific name	Common name	Contaminants	Results	Reference
Phytodegradation	*Blumea malcolmii*	Blumea	Malachite green (after 24 h, a 93.41% decolorization)	Industrial waste phytodegradation	Kagalkar et al. (2011)
	Pueraria thunbergiana	Kudzu	DDT	DDT dehalogenation via reduction	Garrison et al. (2000)
	Chlorella pyrenoidosa	Unicellular green algae	Pentachlorophenol	The cycling of light exposure may have decreased algae activity	Headley et al. (2008)
	Erythrina crista-galli	Cockspur coral tree	Petroleum	Variations in the anatomical makeup of roots	de Farias et al. (2009)
	Phragmites australis	Perennial reed grass	Ibuprofen	*P. australis* can be a useful plant for wetland building	Y. He et al. (2017)
	Spirodela polyrhiza	Duck weed	Ofloxacin (OFX)	Reduced OFX by 93.73–98.36%	V. Singh et al. (2019)
Rhizodegradation	*Tripsacum dactyloides*	Eastern gamagrass	Herbicides (atrazine)	Degradation of atrazine (ATR) was accelerated by 84–60%	C. H. Lin et al. (2011)
	Cynodon dactylon	Bermuda grass	Total petroleum hydrocarbons	81% of the total petroleum hydrocarbons (TPHs) have been degraded	Matsodoum Nguemté et al. (2018)
	Kandelia candel (L.) Druce	Mangrove	Phenanthrene (Ph) and pyrene (Py)	Ph (47.7%) and Py (37.6%) dissipated in the rhizosphere	Lu et al. (2011)
	Melia azedarach	Chinaberry tree	Benzo(a)pyrene	To degrade benzo(a)pyrene, a Cd-resistant plant is necessary	Kotoky and Pandey (2020)
	Rubus fruticosus	European blackberry	Polycyclic aromatic hydrocarbons (PAHs)	Natural-grown blueberries degrade high molecular weight PAHs	Alagić et al. (2016)
	Salix nigra	Black willow	Perchlorate	Rhizodegradation is accelerated using organic carbon	Yifru and Nzengung (2008)

Phytodesalination	*Typha latifolia*	Cattail	Na^+, Cl^-	Irrigation may accelerate the bioaccumulation of contaminants	Xu et al. (2019)
	Sesuvium portulacastrum	Sea purslane	Na^+	*S. portulacastrum* in dry areas; Na^+ buildup is more suited	Rabhi et al. (2010)
	Alternathera philoxeroides	Alligator weed	Na^+	The phytodesalination capacity of alligator weed is 105 kg Na^+ ha^{-1}	Islam et al. (2019)
	Ludwigia adscendens	Water primerse	Na^+	*L. adscendens* produce 80 kg Na^+ ha^{-1} of plant-based desalination	Islam et al. (2019)
	Lonicera japonica Thunb	Honeysuckle	Na^+	Honeysuckle is favorable to Na^+ leaching	K. Yan et al. (2016)

concentrations below the limits that are fatal (Hall 2002). Plants can restrict and limit the uptake and transfer of heavy metals into their tissues through a method called avoidance (Dalvi and Bhalerao 2013). Different defense mechanisms (metal precipitation, exclusion, and root sorption) are used in this process (Dalvi and Bhalerao 2013). The mechanism of root sorption contributes to the immobilization of plants when they come into contact with heavy metal.

3 Approaches to Phytoremediation

The interaction and buildup of heavy metal in the plant are caused by a number of processes, including phytoextraction, phytodegradation, phytostabilization, phytovolatilization, and rhizodegradation (Sarwar et al. 2017). The underlying mechanisms are briefly described and explained in Fig. 2.

3.1 *Phytoextraction*

The intake of heavy metals and their migration to higher portions of the plants, for example, the stems, leaves, and other parts, are included in phytoextraction (Saleem et al. 2020a, b). Research reviews reveal that a variety of hyperaccumulator metallophytes have a lot of potential for the treatment of heavy metal-contaminated soils (Jakovljević et al. 2016).

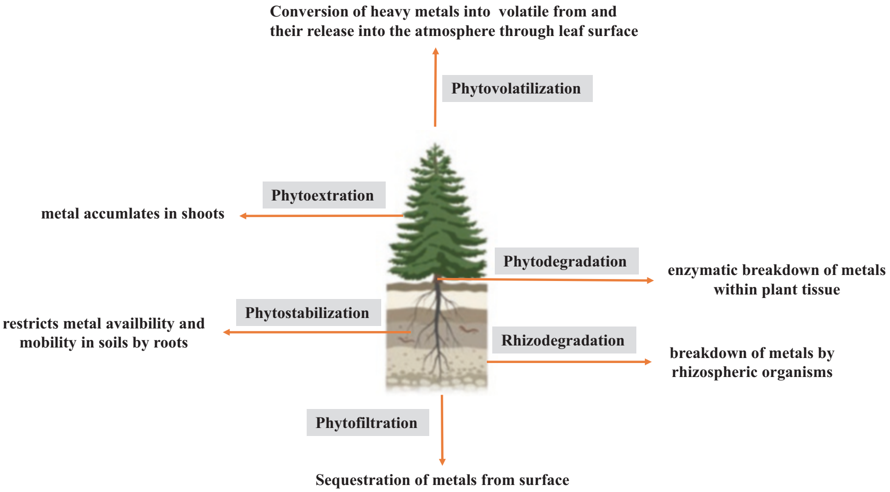

Fig. 2 Methods for phytoremediation and the destinations of contaminants

The kind and quantity of chelators control how quickly hyperaccumulators sequester heavy metals in vacuoles (Saleem et al. 2020a, b). Currently, synthetic chelators are being added to increase mobility and absorption, increasing the effectiveness of phytoextraction. Two important traits that characterize plant species from a phytoextraction perspective are their ability to accumulate heavy metals and surface-based biomass; as a result, plants that have high aboveground biomass production and hyperaccumulate heavy metals are used in phytoextraction (Ali et al. 2013). Additionally, it has been discovered that some of these species have the capacity to accumulate multiple elements, such as *Sedum alfredii* (Bing 2002). Scientific studies are currently being conducted all over the world to increase the efficiency of phytoextraction, where new hyperaccumulators are being targeted to better understand their biological channels. Brassicaceae, Asteraceae, Violaceae, Euphorbiaceae, Fabaceae, and Flacourtiaceae are the plant groups that have been shown to collect higher quantities of heavy metals. Brassicaceae species have demonstrated exceptional potential to remove and scavenge heavy metals, including nickel, cadmium, lead, and zinc (Robinson et al. 1998).

3.2 Rhizofiltration

Rhizofiltration makes use of the roots to collect, hold onto, and settle metal pollutants within the roots, limiting their passage into various environments (Midhat et al. 2019). The settling of metal pollutants on the root surface is greatly influenced by environmental parameters in the root microbiome, including the rhizosphere's pH, root turnover, and root exudates (Zhu et al. 1999). *Mycobacterium* spp., *Pseudomonas aeruginosa*, and *Rhodococcus* spp. are the most often utilized bacteria in rhizoremediation (Verma and Rawat 2021). Rhizoremediation success is greatly influenced by environmental elements such soil type, pH, temperature, and plant species (Sharma et al. 2018).

Plants from both terrestrial and aquatic can be employed for rhizofiltration. Hyacinth, duckweed, azolla, poplar, and cattail are some examples of aquatic organisms that are frequently used to treat wetland water because of their high capacity for accumulation, high carrying capacity, and higher biomass output (Hooda 2007). Similar to this, terrestrial plants (*H. annuus* and *B. juncea*) exhibit a significant capacity to accumulate heavy metals during rhizofiltration due to their larger hairy root systems (Dhanwal et al. 2017); studies have shown that sunflower has a remarkable capacity to detoxify Pb-contaminated locations (Raskin and Ensley 2000).

3.3 Rhizodegradation

Organic contaminants degrade through a process called rhizodegradation in the soil and are biodegraded in conjunction with rhizospheric microorganisms that release certain enzymes that either break down or change very polluted organic pollutants into safer forms (Li et al. 2016). One of the essential components of rhizodegradation, which emphasizes the complete mineralization of the organic pollutants following compound transport to the plant or atmosphere, is the dissolving of the pollutant at the source (Fiorentino et al. 2018). Rhizodegradation has a number of drawbacks, including the fact that it is a slow, drawn-out process that only functions up to a certain depth, typically between 20 and 25 cm. Rhizodegradation is impacted using the type of soil and specific plant species (Kaimi et al. 2006).

3.4 Phytostabilization

Inhibiting contaminant movement into underground water and preventing biomagnifications are achieved through the processes of phytostabilization and phytorestoration (Van Oosten and Maggio 2015). For the stability of toxins in polluted environments, the procedure mostly relies on the use of particular plants (D. Singh et al. 2012). These remediation techniques have been successful in reducing the mobility of pollutants in soil environments (Mench et al. 2010). Insoluble chemicals are created in the rhizosphere as a result of the process (Burges et al. 2018). The metallophytes are used to successfully recover polluted sites, and they are suitable for removing metals like Cu, Zn, As, Pb, Cr, and Cd (Yang et al. 2016). Phytostabilization serves to immobilize and inactivate potentially harmful pollutants. As long as contaminants are present in the soil, it is merely a temporary management strategy that restricts the flow of metal ions (Gong et al. 2019). The plant must be able to adapt to various soil conditions and develop quickly with a long life span for phytostabilization to be effective (Cunningham and Berti 2020). Numerous investigations have demonstrated that Pb, Zn, and Cd can be eliminated using medicinal and aromatic plants (Saha and Basak 2020).

3.5 Phytodegradation

Organic pollutants isolated by the plant across the variety of metabolic processes or that have been broken down by the enzymes that are a part of the plant's metabolism are called phytopollutants (P. Sharma and Pandey 2014). Various plants can be employed in this process; the most popular ones are *Leucocephala* for ethylene dibromide (Doty et al. 2003) and sunflower (*Helianthus annuus*) for methyl benzotriazole (Castro et al. 2003). This method is restricted in that the soil must be 3 feet deep and the groundwater must be no more than 10 feet below the surface. Chelating agents are required to increase plant absorption using attaching pollutants to soil particles (Miller 1996).

3.6 Phytovolatilization

By using the stomata to help with transpiration, phytovolatilization is the process by which pollutants are converted into various volatile chemicals and released into the atmosphere (Leguizamo et al. 2017). Commonly utilized plants for phytovolatilization include *Nicotiana tabacum*, *Arabidopsis thaliana*, *Trifolium repens*, *Crinum americanum*, *Bacopa monnieri*, and *Triticum aestivum* (R. Singh et al. 2018). Either a direct or indirect approach can be taken. Volatile organic compounds are directly vaporized by leaves, and the stem, whereas plant root interactions with the soil cause indirect volatilization (Limmer and Burken 2016). Organic pollutants like acetone, phenol, and chlorinated benzene (BTEX) are all degraded by phytovolatilization (Herath and Vithanage 2015). The phytovolatilization technique yields the most positive results for mercury (Hg) and selenium (Se) (Ahmadpour et al. 2012).

Phytovolatilization is the most contentious technique of phytoremediation (McCutcheon and Schnoor 2003). As a remediation strategy, phytovolatilization just speeds up the transfer of pollutants, which can occasionally contaminate the surrounding atmosphere as they rise from the soil. Additionally, precipitation has the ability to redeposit these into the soil (Vangronsveld et al. 2009).

3.7 Phytodesalination

The most popular biological option for decontamination is phytodesalination, a recently developed and emerging technology that uses halophytic plants to repair saline soils (Ali et al. 2013). There is not much information available about this procedure in the researches when compared to the other phytoremediation methods. As compared to glycophytic plants, halophytes are thought to be naturally well-adapted to heavy metals (Manousaki and Kalogerakis 2011; Singh et al. 2023). The plant’s ability to phytodesalinate depends on the species as well as on the salinity, sodicity, and porosity of the soil as well as other environmental variables, mainly rainfall (Hussain et al. 2018). According to a review of the literature, two halophytic plants, *Suaeda maritima* and *Sesuvium portulacastrum*, can each take almost 504 and 474 kg of NaCl from a hectare of saline soil over 4 months (Ravindran et al. 2007). The remediation of soil impacted using chloride, and sodium ions have been reported to exhibit encouraging outcomes in desalination tests of halophytic plants (Singh et al. 2023). The decontamination of soils contaminated with heavy metal and polycyclic aromatic hydrocarbons is not appropriate for this bioremediation technology; nonetheless, it is promising for soils impacted by salinity (Zorrig et al. 2012).

4 The Progression of Genetic Engineering

Genetic engineering has been an important strategy for enhancing plants' ability to clean up heavy metal contamination through phytoremediation. With the use of genetic modification, a foreign gene from another organism is moved and installed into the target plant's genome, followed by DNA recombination, which grants the plant specific features in a shorter amount of time (Marques et al. 2009).

Exertion has demonstrated a lot of potential for phytoremediation. However, knowledge about plants' heavy metal tolerance and accretion mechanisms should be taken into consideration when choosing genes. The exaggeration of genes entangled in the antioxidant mechanism (Koźmińska et al. 2018). Similar to this, heavy metal chelators can be produced through genetic engineering to improve heavy metal uptake and translocation (G. Wu et al. 2010). Although the use of genetic engineering has shown promising results in phytoremediation, there are still several issues that need to be resolved. Since their use raises questions about the safety of food and ecosystems, genetically modified plants sometimes struggle to obtain clearance and approval in some parts of the world. This calls for alternate strategies that, if genetic engineering proves to be impractical, could augment and increase species of plants' performance utilized in phytoremediation. The many studies about genetically modified plants utilized in phytoremediation are summarized in Table 2.

Table 2 Use of genetically modified plants in phytoremediation

Scientific name	Common name	Contaminants	Nature of contaminants	Reference
Grass *Polypogon monspeliensis*	Rabbitfoot	As	Releases dimethylchloroarsine ($AsCl(CH_3)_2$) and pentamethylarsine ($As(CH_3)_5$)	Ruppert et al. (2013)
Juncus efuses	Common rush	Artificial sewage	Methane and ammonium are emitted	Wiessner et al. (2013)
Phragmites australis	Perennial need grass	Organochlorines	1,2,4-Trichlorobenzene (TCB), γ-hexachlorocyclohexane (γ HCH), and 1,4-dichlorobenzene (DCB) are volatized	San Miguel et al. (2013)
Brassica juncea	Mustard	Se	Additionally, *Brassica* spp. may cause Se to be phytovolatilized	Banuelos et al. (1997a, b)
Scirpus robustus	Saltmarsh bulrush	Se	Plants in wetlands	Arthur et al. (2005)
Arabidopsis thaliana	Thale cress	Cd, Pb	Cd and Pb tolerance	Song et al. (2003)

5 Phytoremediation of Inorganic and Organic Compounds

The word “phytoremediation” is a broad term and includes a wide range of methods used by plants to reduce, eliminate, or stabilize pollutants in water, soil, or the environment (Song et al. 2003). This technology incorporates natural mechanisms that plants and the related microbes breakdown and/or sequester inorganic and organic pollutants shown in Table 3, making it a less expensive and more ecologically friendly alternative to existing techniques of removing toxins from soil (Nwoko 2010). The results of studies on the potential of phytoremediation demonstrate that it can be used to remove a variety of pollutants, such as metals (Jadia and Fulekar 2009), organic compounds, radionuclides such as chlorinated solvents, toluene, xylene, ethylbenzene, polychlorinated biphenyl and BTEX-benzene (Chen et al. 2010), polyaromatic hydrocarbons (PAHs) (Denys et al. 2006), and pesticides (Chang et al. 2005). The ability of plants to ingest and/or collect organic and inorganic pollutants in their cellular structures, as well as to carry out profound oxidative degradation of organic xenobiotics (Kvesitadze et al. 2009), is necessary for phytoremediation to be successful. Although it may be feasible to overcome this by employing species with a quick growth cycle and high biomass (Olson et al. 2007), the primary disadvantage of phytoremediation is the amount of time it takes to reach the target concentrations.

5.1 *Phytoremediation of Organic Compounds*

Organic pollutants can be released into the urban systems by a variety of industrial processes, including the treatment of wood (Robinson and Anderson 2007), oil prospecting (Rogge et al. 1997), benzene, trichloroethylene (TCE), polyaromatic hydrocarbons (PAHs), xylene (BTEX), and others. Due to their extensive occurrence as a result of human activities and by-products of significant industrial processes, like the pyrolysis reaction, PAHs are the most prevalent organic pollutant in contaminated soils (dos Santos Barbosa et al. 2006). The fact that organic molecules come in a variety of structural and chemical configurations makes them difficult to remediate. The chemicals must be converted into nontoxic molecules, such as NH_4^+, NO_3^-, CO_2, and Cl^- (Meagher 2000), in order for phytoremediation to occur. With increasing molecular weight, they become less soluble (Werner 2003) because they become more hydrophobic and may get swollen to the soil (Neuhauser et al. 2006).

Pollutants move through the plant with transpiration fluid during the passive process, while transporters like carrier proteins are engaged in active transport (Nardi et al. 2002). This mechanism, which results in sluggish desorption of organic pollutants and little microbial decomposition, is crucial to the fate and transit of PAHs in soil (Hwang and Cutright 2002). Organic chemicals may become less labile and bioavailable as they deteriorate in soil; however, this would have less of an impact on their overall concentration. For instance, Cofield et al. (2008) found that the

Table 3 Selected examples of phytoremediation trials for different types of contaminants

Type of contaminants	Pollutants	Soil concentration (mg kg^{-1})	Scientific name of plant	Growth circumstances	Modification	Measure of success	Reference
Organic	PAH	1251.7	*Triticum aestivum*, *Zea mays*, *Vicia faba*	Field	None	PAH dissipated	Diab (2008)
	TPH	6400	*Lolium perenne*	Glasshouse	None	Loss of TPH	Hou et al. (2001)
	TNT	80	*Vetiveria zizanioides*	Spiked/ glasshouse	Urea	Urea aided in the removal of TNT	Das et al. (2010)
	Chrysene	500	*Trifolium repens* L, *Lolium perenne*	Spiked soil/ glasshouse	None	Degradation of chrysene	Johnson et al. (2004)
Inorganic	Zn, Cd	Zn-600, Cd-8	*Pennisetum atratum*, *Pennisetum americanum*	Spiked soil/ glasshouse	Basic fertilizer	Removal of metal	X. Zhang et al. (2010)
	Cd	1.6 ev	*Averrhoa carambola*	Field	N		J. Li et al. (2009)
	Zn, Cd, Pb	Zn –500, Cd-20, Pb-1000	*Vetiveria zizanioides*, *Dianthus chinensis*	Greenhouse	EDTA	Increased metal removal with EDTA	Lai and Chen (2004)
	Cu	1200	*Elsholtzia splendens*	Field, greenhouse	KH_2PO_4, urea	Removal of Cu	Jiang et al. (2004)
	Pb	20	*Vetiveria zizanioides*	Greenhouse	EDTA	Removal of metal	Gupta et al. (2008)

Mixed	Cu, PCD	Cu-300, PCP-100	*Lolium perenne* L., *Raphanus sativus*	Spiked/ glasshouse	Fertilized	PCP dissipates more quickly below 50 mg/kg as the concentration of copper rises	Q. Lin et al. (2006)
	Cu, PCP	Cu-300, PCP-100	*Lolium perenne* L., *Raphanus sativus*	Spiked/ glasshouse	Fertilized	PCP dissipates more quickly below 50 mg/kg as the concentration of copper rises	Q. Lin et al. (2006)
	Pyrene, Cd	CD-4.5, Pyrene-100	*Zea mays*	Spiked/ glasshouse	Fertilized: NPK	Pyrene uptake is increased when Cd is present	H. Zhang et al. (2009a, b)
	Cd, pyrene, phenanthrene	Cd-50, Phenathrene-250, Pyrene-250	*Juncus subsecundus*	Spiked/ glasshouse	Fertilized	Cd has an impact on how PAH dissipates	Z. Zhang et al. (2011)

TPH total petroleum hydrocarbons, *EDTA* ethylenediaminetetraacetic, *PAH* polycyclic aromatic hydrocarbons, *PCP* pentachlorophenol, *TNT* 2,4,6 trinitrotoluene.

non-labile PAHs were unaffected whereas the total PAHs in the soil dropped when *Festuca arundinacea* and *Panicum virgatum* were present.

5.2 Phytoremediation of Inorganic Contaminants

In contrast to organic pollutants, which can be mineralized or decomposed, inorganic contaminants are made of minerals (Cunningham et al. 1996). Some plants are capable of transmitting, stabilizing, or collecting inorganic substances. For the latter, the plant species just has to tolerate the inorganic compounds and refrain from absorbing them, whereas hyperaccumulator plants have shown the capacity to accumulate large amounts of inorganic compounds and afterward eliminate the pollutants from the soil for the former (Ghosh and Singh 2005). Nickel is accumulated by the majority of hyperaccumulators, but others accumulate manganese, cadmium, zinc, and cobalt. One of the most researched hyperaccumulators is the zinc and cadmium hyperaccumulator, viz., *Thlaspi caerulescens* (A. S. Wang et al. 2006). Metal speciation within the soil is essential for preventing metal absorption. With the exception of mercury, plants may take up metals from the aqueous phase. Even when some critical metals are not present, there are signs of increased metal uptake in non-accumulating plants. One way that this happens is when plants alter the rhizosphere, releasing phytosiderophores or increasing acidity to make some metals more mobile (Marschner 2011). During the phytoremediation of inorganics, microbial communities in the rhizosphere may also be crucial (Whiting et al. 2001). Numerous glasshouse and laboratory investigations on the phytoremediation of inorganics have been successfully completed, as indicated in Table 3.

5.3 Phytoremediation of Organic-Inorganic Mixed Contaminated Soils

Since most sites are exposed to both organic and inorganic pollutants, phytoremediation of mixed polluted soils is essential (Chigbo et al. 2013). Phytoremediation may be impacted by the interaction of pollutants with one another, with plants, and with the rhizosphere when they are mixed or combined (Chigbo and Batty 2013). Additionally, it has been shown that dangerous metals like Cd, which promote microbial activity, significantly restrict the biodegradation of organic pollutants (Maslin and Maier 2000). The presence of appropriate, active microorganisms and favorable environmental conditions are crucial for the phytoremediation process because they facilitate the degradation of organic contaminants. Heavy metals were found to reduce the diversity and number of particular populations of microorganisms, according to (Dobler et al. 2000). Additionally, it has been demonstrated that mixtures of organic and inorganic pollutants have detrimental consequences, including toxicity and an impact on plant growth. Chigbo and Batty (2013) revealed in a field investigation that the presence of metals like Pb, Cu, and Zn improved the elimination of hydrocarbon by *Populus deltoides* x *wettsteinii* and *Pinus sylvestris*. However, toxicity caused around 80% of the trees to perish. *Zea mays* L.'s root and shoot pyrene accumulation was demonstrated to be improved by cadmium, while plant-promoted rhizosphere biodegradation was found to be more crucial for pyrene dissipation (H. Zhang et al. 2009a, b), and utilizing a variety of plant communities could help solve the co-contamination problem. According to research, the microbial community in a plant's connected rhizosphere is influenced using the diversity of the plant (Kowalchuk et al. 2002).

6 Factors Affecting the Metal Uptake

Numerous variables such as plant species, temperature (Liao and Chang 2004), pH, the root zone (Sarma 2011), the addition of chelators, and cation exchange capacity (CEC) influence the accumulation of heavy metals using plants. These environmental factors' effects are described in Fig. 3:

Plant Species It is decided to use plant species with varying potentials for different cleanup techniques. Faster development in terms of plant mass, root depth per unit volume, lateral extension, and surface area is emphasized by processes such as rhizodegradation, rhizofiltration, and phytostabilization (Hasan et al. 2019), because it can extract and remove sizable amounts of heavy metals from sterile material. *Robinia pseudoacacia*, for instance, can be utilized successfully and ecologically to

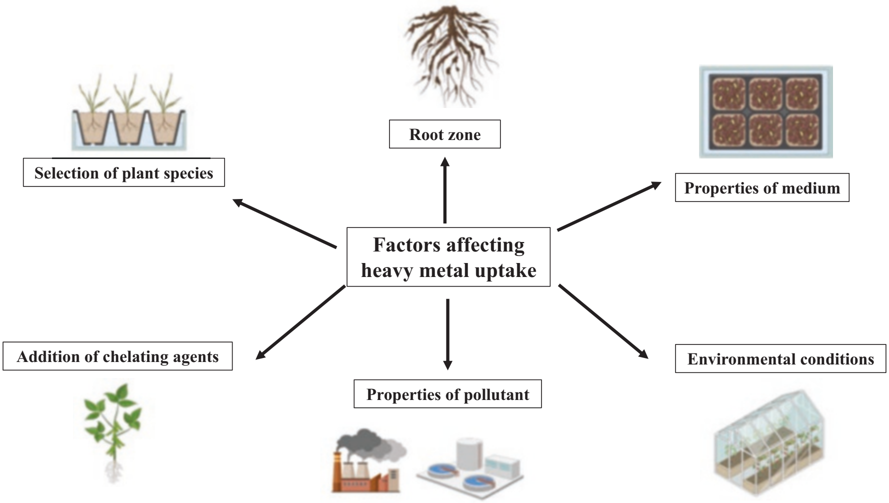

Fig. 3 Elements affecting the absorption of heavy metals

remediate sterile wastes (Babau et al. 2020). By producing enzymes and root exudates, the rhizobium should promote microbial development. Additionally, plants should have strong remediation potential, adequate biomass yield and storage, rapid growth, high waterlogging tolerance, and resilience to high salinity and pH (Gerhardt et al. 2017).

pH It is considered to be among the most significant impacting variables in retention and the solubility of heavy metals in soil. Higher pH results in more retention and less solubility (Basta and Gradwohl 1998), while lower pH makes hydrogen ions more accessible. For instance, pH has a significant impact on how well plants absorb Pb. With the use of lime, soil pH is raised to values between 6.5 and 7.0 in order to decrease the uptake of Pb by plants (Anton and Mathe-Gaspar 2005). Plants can raise the bioavailability of heavy metals by using root exudates to alter the pH of the rhizosphere and increase the solubility of the metals (A. Yan et al. 2020). The metal is subsequently absorbed at the metal surface and diffuses into the root cells via symplastic (active diffusion) and apoplastic (passive diffusion) channels through the cell membrane (Plant and Raiswell 1983). The solubility of metals is significantly influenced by soil pH and soil properties. Most heavy metals are easily transportable in acidic and oxidizing settings, but they are substantially maintained in alkaline and reducing environments (Brümmer and Herms 1983). Zn, Pb, Cu, Cd, Hg, and Co are all more soluble at pH 4–5 than they are in the range of pH 5–7 (Gerritse and Van Driel 1984).

Root Zone The root zone is crucial to phytoremediation because it metabolizes and absorbs down contaminants inside plant tissue or by releasing enzymes to break them down (Babau et al. 2020). The rate of cleanup must be based on the root zone. For instance, the fibrous root system contains a large number of little roots that cover impacts the entire soil, and offer a larger surface area, enhancing the plant's ability to make the greatest possible contact with the soil (Kvesitadze et al. 2006). Another phytoremediation method is the detoxification of soil pollutants using plant enzymes released from the roots (Benjamin and Leckie 1981).

Cation Exchange Capacity (CEC) CEC gauges the quantity of cations that can be maintained on soil particle surfaces or the rate of metal adsorption at the soil interface. Calcium absorption is decreased when Pb and Cu are added, according to research conducted by the scientific community (Salt et al. 1998).

Addition of Chelators Chelating agents are known to increase or speed up the uptake of heavy metals and are, therefore, known to be the cause of induced phytoremediation (Van Ginneken et al. 2007). Chelators have been employed to make metals more soluble, which might significantly increase the amount of metal that accumulates in plants.

Temperature A notable aspect that influences how much metal plants take up is soil temperature (Q. Wang and Cui 2011). For instance, a significant increase in the Cd and Zn content of sorrel and maize shoots has been documented during high temperatures and low soil pH (Sinha et al. 2013).

7 Plant Assortment Benchmarks for Phytoremediation "Candidate Plants"

Numerous plants have been employed to examine phytoremediation of xenobiotic contaminants in urban ecosystems, including poplar, *Leucaena*, rye grass, fescue, rice, and Indian mustard. Poplar trees provide excellent candidate for phytoremediation plants, according to a number of lines of evidence, as they produce a lot of biomass, have deep roots, and can withstand both organic and inorganic contaminants (Burken and Schnoor 1997). In phytoremediation, elements like root complexity, soil contaminants, soil, and local climate are crucial. Numerous studies have revealed that plants with shorter growing seasons than perennial plants are a better choice to be used in phytoremediation (Tordoff et al. 2000). It has also been advised to utilize species of plants that are appropriate to the regional or local soil characteristics of the location where decontamination is to be carried out (Compton et al. 2003). Because they are naturally equipped to withstand the stress conditions of the area and have low preservation costs, noninvasive species of plants should be chosen. In addition, native plants are more hospitable to humans and the environment than alien species (Haq et al. 2020). Additionally, according to numerous scientific studies, grasses grow more quickly than trees and shrubs, produce a large amount of biomass, are more resilient, and are better able to clean up different types of soil (Verbruggen et al. 2009).

8 Plants Known to Utilize in Phytoremediation

Organic and inorganic pollutants from soil can be eliminated by plants (Dary et al. 2010). The contaminant, the soil, and species of plants all affect the effectiveness of remediation. The efficiency of remediation is significantly influenced by plant biomass and metabolism, which in turn is influenced using electric conductivity, soil pH, organic matter content, microbial activities, and various soil enhancements (Anton and Mathe-Gaspar 2005; Guidi Nissim et al. 2018). The translocation factor, which is the ratio of elemental accumulation in the plant's shoot compared to plant's root, and the bioconcentration factor, which is the ratio of pollutant concentration in the plant parts to that in the medium, are typically used to assess the phytoremediation potential of the plants (Q. Wu et al. 2011).

9 Advantages of Phytoremediation

Because they make use of solar energy and the physiological processes of the plant, plants provide an environmentally benign alternative to the decontamination technologies and traditional ways for cleaning up the environment (Susarla et al. 2002).

Plants have the ability to reduce contaminants in a variety of media, including soil, air, and water. The use of phytoremediation may indirectly improve carbon sequestration since planting more plants to remove harmful contaminants from the environment will reduce atmospheric carbon dioxide levels. When phytoremediation and sustainable site management are integrated, the result is a larger range of advantages for the economy, the environment, and society as a whole (Burges et al. 2018). Some researchers proposed for the idea of tying phytoremediation to ecosystem services like carbon sequestration, fertility, water flow, and water purification. These services also include nutrient recycling (Tully and Ryals 2017). Monitoring metrics such as texture, pH, exchange capacity for cations, and the quantity and variety of the microbial community will reveal the indicators that represent the functionality and quality of the restored soil. Ecological risk assessment is used to evaluate the condition of the soil in a phytoremediated region, and Gutiérrez-Ginés et al. (2014) suggested the idea of long-term monitoring programs for the prediction of phytomanagement success. Table 4 shows many of the pros and cons of phytoremediation technology.

10 Limitations of Phytoremediation

Although phytoremediation offers a powerful alternative technique for removing contaminants from the urban ecosystems, it has a number of restrictions and disadvantages. For starter, the majority of research is done quickly and in a controlled atmosphere. This might not produce results that are true representative, even if it were done for a long time in the field. In order to determine the full potential of phytoremediation, more field studies based on longer time frame are required. Another drawback is that the success of phytoremediation is dependent on the plant species' ability to develop quickly and successfully. The exact phytoremediation method used for one type of plants at one site could not be effective at another due to differences in the soil and temperature at each location. It is therefore site-specific. In addition to soil and climate, other living things and microbes (pests, pathogens, and insects) on the site may have an impact on a plant's physiology. Combining viruses, insects, and pests with contaminants like heavy metals, organic pollutants, antibiotics, or radionuclides may render plants more susceptible to disease and imperil phytoremediation efforts. Additionally, plants can only grow at specific levels of pollutant concentration. The phytoremediation capacity of plants may be impacted by their slower growth due to their sensitivity to greater levels of pollutants (Greenberg 2001).

11 Field Testing and Risk Assessment

When creating transgenic plants, it's crucial to weigh factors like field testing and risk evaluation. Transgenic plant phytoremediation may have some benefits, although research on the potential biosafety risks is lacking (Davison 2005). Except for those created for herbicide degradation, no transgenic plant created for

Table 4 Pros and cons of phytoremediation technology

Phytoremediation techniques	Advantages	Limitations	Reference
Phytoextraction	Plants that produce hyperaccumulators can serve as resources	These plants grow more slowly, produce less biomass, and have shallow root systems There is a chance that certain metals will be phytotoxic	Newman (1997); Adams et al. (2000); Ghori et al. (2016)
Phytostabilization	It is an inexpensive and less disruptive technique Replanting helps the ecosystem recover	To prevent pollutant release, metal absorption, and transport to aboveground components, soil, vegetation, root zones, and root exudates must be continuously monitored Soil removal as well as hazardous materials and biomass are not necessary. Phytostabilization is seen as a stopgap action	
Rhizofiltration	Plants from both the land and the water can be utilized The methods employed are either ex situ (a designed tank system) or in situ (floating rafts on ponds)	For optimum metal absorption, a well-engineered design is necessary to regulate influent concentration, pH, flow velocity, chemical speciation, and interaction with other species	
Phytovolatilization	When contaminants are discharged into the atmosphere, they can be more efficiently analyzed, such as via photodegradation	A harmful metabolite or pollutant may build up in plants and then be transferred to subsequent goods like fruit or lumber. Low metabolite concentrations Been discovered in plant tissue	
Phytodegradation	A plant's enzymes may break down pollutants in an environment devoid of microorganisms	Toxic degradation or intermediate products are produced	
Rhizodegradation	Degradation of contaminants happens in situ and at the source Mineralization of the contaminant can happen	Although the end extent or degree of degradation may be identical in rhizosphere and non-rhizosphere soil, the rhizosphere might affect an increase in the beginning degradation rate when compared to a non-rhizosphere soil For a wide root zone to form, considerable time is needed	

phytoremediation of refractory xenobiotic contaminants has yet been commercially used. The risks connected to xenobiotic pollutant degradation by plants need to be thoroughly investigated (Davison 2005), and the degraded materials need to be less dangerous than the original contaminant. Prior to commercialization, it is also necessary to consider the risk of xenobiotic pollutant volatilization. Additionally, using chloroplast transformation to create transplastomic plants helps minimize the issue of genes escaping from transgenic plants to distant relatives or crop plants. Use of unpalatable species and appropriate fencing off of the area can help prevent some of the risk of wild animals ingesting transgenic plants.

12 Conclusions and Future Perspectives of Phytoremediation

One of the major worldwide issues affecting ecosystems, biodiversity, and human health is the organic and inorganic xenobiotics. Phytoremediation technology breaks down xenobiotics from urban ecosystems to become a less disruptive, more cost-effective, and environmentally friendly cleaning technology. Additionally, phytoremediation only requires a limited amount of specialized involvement and can be used for a long time. Transgenic techniques can be used to improve the molecular capacity of several plant species for cleanup. Genetically engineered species that have exhibited noticeably high tolerance and metal absorption capacity have been successfully created using gene editing, alteration, and deletion approaches. It will offer fresh and cutting-edge research techniques for improved outcomes through the following:

- Research into whether plants are highly resistant is necessary to determine whether they are appropriate for particular environmental circumstances. For the first identification of such species, in situ toxicity testing may be helpful.
- Comparing the phytoremediation technique to physicochemical methods, the phytoremediation technology symbolizes a practical and viable option to get benefits in both monetary and environmental terms.
- In the near future, the application of this method for soil remediation can be improved by more thorough investigations into the potentials and limitations of phytoremediation.
- Finally, the usage of genetically engineered plants can further take advantage of this plant-microbe relationship and provide quick solutions for cleanup.

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